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Final Degree Thesis

An approach to Energy Planning in Germany - Energy Transition towards a low-carbon economy

Analysis and application of Modern Portfolio Theory to the German Electricity Mix

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Abstract

The targets of this Final Degree Thesis are to explain the current situation of the German Energy Sector, its evolution over time, to compare its features with the European Union Energy Sector, and finally, to forecast how it will be in future years according to a Markowitz optimization portfolio model.

The study contextualizes the current characteristics of the German Energy sector, such as: composition of its energy mixes (both primary energy mix and electricity mix), energy demand, German energy consumers, infrastructure and pollution, always comparing these variables with the European Union´s Energy Sector.

In order to understand the behavior of the previous variables over time, the regulation framework at both a national level and a European level is developed. So as to highlight how these guidelines and some other relevant events, such as the current SARS-CoV-2 outbreak, will define the German Energy Transition.

Using Modern Portfolio Theory and applying the appropriate restrictions, a forecast of the electricity mix composition for the years 2030, 2040 and 2050 and the implications that it has in terms of power prices, pollution and health was made: by 2030, 65% of the electricity produced in the country will be generated by RES and Biofuels, by 2040, 65%-82%, and by 2050 this proportion will reach 80%-90%. Also, Conventional Energy Sources are expected to be less important as time passes. In contrast, all Green Energy Sources will be improved drastically, being way more competitive in terms of production costs than Fossil Fuel Sources, indeed, Onshore Wind will become the single largest energy source, generating 31%-65% of power in the country, followed by Solar (13%-28%).

Key Words: German Energy Sector; Markowitz optimization portfolio model; Primary Energy Mix; Electricity Mix; German Energy Transition; Modern Portfolio Theory; Renewable Energy Sources.

Resumen

Este Trabajo de Fin de Grado tiene como objetivos definir la situación actual del sector energético alemán, su evolución a lo largo del tiempo, comparar sus características con el sector energético de la Unión Europea y estimar cómo será el sector energético nacional en las próximas décadas, de acuerdo con el Modelo de optimización de carteras de Markowitz.

El estudio contextualiza las características actuales del Sector Energético Alemán, tales como: composición de sus mixes energéticos (tanto mix de energía primaria como mix eléctrico), demanda energética, consumidores energéticos alemanes, infraestructura y contaminación, comparando siempre estas variables con el Sector Energético de la Unión Europea.

Para comprender el comportamiento de las variables anteriormente mencionadas a lo largo del tiempo, se desarrolló el marco regulatorio a nivel nacional y europeo, destacando como estas directrices y otros eventos relevantes, como el actual brote de SARS-CoV-2, definirán la Transición Energética Alemana.

Mediante el uso de la Teoría Moderna de Cartera y aplicando las restricciones apropiadas, se pronosticó la composición del mix eléctrico alemán para los años 2030, 2040 y 2050, y las implicaciones que esto tiene en términos de precios de la electricidad, contaminación y salud: en 2030, el 65% de la electricidad producida en el país será generada por fuentes de energía renovables y biocombustibles, para 2040, el 65%-82%, y para 2050 esta proporción alcanzará el 80%-90%. Además, se espera que las fuentes de energía convencionales sean menos importantes a medida que pase el tiempo. Por el contrario, las energías verdes se verán mejoradas drásticamente, siendo más competitivas en términos de costo de producción que las fósiles, de hecho, la eólica se convertirá en la mayor fuente eléctrica, generando el 31%-65% de la electricidad, seguida por la Solar (13%-28%).

Palabras clave: Sector energético alemán; modelo de optimización de carteras de Markowitz; mix de energía primaria mix eléctrico; Teoría Moderna de Carteras; transición energética alemana; fuentes de energía renovables.

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List of Abbreviations

CCUS	Carbon Capture, Utilization and Storage
CO_2	Carbon dioxide
EEG	German Renewable Energy Sources Act, *Erneuerbare-Energien-Gesetz*
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIC	Gross Inland Consumption
Gt	Gigatonnes
GW	GigaWatt
GWh	GigaWatt Hour
kWh	Kilowatt Hour
LCOE	Levelized Cost of Electricity
MWh	Megawatt Hour
Mtoe	Million Tonnes of Oil Equivalent
OECD	Organization for Economic Co-operation and Development
PV	Photovoltaic
RES	Renewable Energy Sources
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
toe	Tonnes of Oil Equivalent
TWh	Terawatt Hour
Wh	Watt hour

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1. Overview of the German Energy Sector

1.1 German Energy Sector Features

Germany is the largest national energy consumer in Europe and 6th largest energy consumer worldwide. Its Gross Inland Consumption (GIC) in 2018 was 314.43 Million Tonnes of Oil Equivalent (Mtoe), representing the 21.3% of the total energy consumption in the European Union (EU) (energy conversion units can be consulted in (Annex A).

It is also the largest national electricity market in Europe, with a production of 641.59 Terawatt Hour (TWh) in 2018, 7,728.21 Kilowatt Hours (kWh) per capita, which was 17.4% more than the EU-27 (EU-27: 6,583 kWh/person) and comparable to the 93.6% of the Organization for Economic Co-operation and Development (OECD) average per capita electricity consumption (8,256 kWh/person).

In 2017, the median German household consumed an average of 3,171 kWh of electricity at 30.5 Euro Cents per kWh, spending a grand total of 80.59 Euros monthly (697.07 Euros yearly) on electricity bills, Germany had the second highest price of electricity in EU only after Denmark.

Germany´s carbon dioxide (CO_2) emissions for the year 2017 summed up to 0.7 Gigatonnes (Gt), being the most CO_2 polluting country in Europe and the 6th in the world. In per capita terms, every German resident polluted 8.7 tonnes yearly, being the most per capita polluters in the European Continent and the 8th in the world. Among all the Greenhouse Gases (GHG) emitted every year in Germany, roughly 80% of which is CO_2, and 35% of which is produced by the Energy Sector.

Its huge size within the European Energy Market has granted Germany the leading role in the EU Green Energy Transition and Energy Market Integration, being a reference in innovation patents, green energy production, legislation and for heavily investing in Renewable Energy Sources (RES) since the beginning of the century.

The regulator is well aware of Germany´s position in the European framework, thus, in 2010 it initiated the so called *Energiewende* (Energy Transition) by passing the *Energiekonzept* (Energy Concept) Document, that sets the energy policy of the country until 2050 in terms of RES, Energy Efficiency, Electricity Production and GHG Emissions.

Its main objectives are improving the energy efficiency of the country by reducing the consumption of energy in all sectors, developing the use of RES (predominantly solar and wind) for electricity production and cutting down the GHG emissions by at least 80% by 2050.

Because of this low carbon energy transition, Germany has followed a phase-out policy regarding nuclear power, expecting to shut down the 8 remaining power plants in the country by 2022.

The main piece of Green Energy Legislation is the German Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz or EEG), a series of laws passed between the years 2000 and 2017, that aim to boost the development of green energy sources in the country by financing part of the generation cost of these technologies through levy’s included in the final electricity prices.

Regarding Germany´s Green Innovations or EcoInnovations it can be said that the country is one of the leaders within the European Environment, being remarkable for its huge energy savings in business (40% of Germany´s have a certain kind of energy saving measures) saving up to the 14% of the energy they use. And for its outstanding number of green startups. Thanks to these features, its large number of eco-innovations patents and for its great waste management, Germany has been awarded the third position in the Eco-Innovation Index in 2017 (O´Brien, 2017).

Notwithstanding, Germany´s lack of energy supply sufficiency is perhaps one of the biggest threats to the European Energy Common Market. Germany imports more than half of its energy, mainly oil (being the 5th largest oil consumer worldwide) from Russia, Norway and the United Kingdom. But also, vast amounts of natural gas, giving the country the spot of world's largest importer of natural gas. As a consequence of this energy deficit, the country drives out resources that could have been used in the European territory, giving influence to countries suppliers of fossil fuels against the EU model such as Russia, and at the same time, waking the demand of Euros by using the United States Dollars in order to pay more than 80% of all energy imports that the EU makes (Guarascio & Zhdannikov, 2019).

Nevertheless, because of its massive coal deposits, Germany has a long-lasting tradition of using coal, and it is nowadays the 4th largest consumer of coal in the world. However, the same does not happen from the production side, due to the efforts of the national regulator to put Germany in the path of an environmentally friendly way of producing energy, the production of coal in the country is more expensive than importing it from countries such as China or Colombia, causing the domestic coal mining to be almost completely phased out.

As a result of this transition seen in the last years, Germany has been called "the world's first major renewable energy economy". Achieving on 8 May 2016 a renewable energy supply of the 87.6% of Germany's national electricity consumption under extremely favorable weather conditions (Coren, 2016).

Accurate policy framework and investment in the appropriate technologies are not enough in order to have a competitive green energy sector integrated in the European Common Market, however, this is not a problem for the country. Germany has got a network of 36,800 Km of extra high voltage lines, that is operated at voltages of 220 and 380 kilovolts, enabling the country to be properly interconnected domestically and with its European neighbors, being a reference in electrical infrastructure due to its size and capacity.

Germany has got grid interconnections with neighboring nations representing 10% of domestic capacity. Thanks to its location, Germany is the center of Europe´s electricity exchange market, sharing border with eight countries (Netherlands, Luxembourg, France, Switzerland, Austria, Czech Republic, Poland and Denmark) and one cross-sea electricity flow (with Sweden) (Bundesverband der Energie- und Wasserwirtschaft, 2019).

Germany is also considered to be the largest exporter of electricity in Europe with net exports of 45.6 TWh with an average price of 38.6 Euro/ Megawatt Hour (MWh) in 2018.

These data contrast with the huge energy deficit that Germany has got, it is a clear symbol of the common European Energy Market, transitioning from an external dependent fuel-based model to a European Interconnected Electricity Market grounded on RES.

However, this quick transition, shutting down all nuclear energy plants by 2022 and encouraging the generation of energy through RES, are not enough to supply all energy necessities of the country, having to heavily rely on gas fossil fuels while facing this energy transition (Kunz & Weigt, 2014).

1.2 Primary Energy Mix and Electricity mix

The energy sector in all countries is composed by two different mixes that cover different fields of energetic needs:

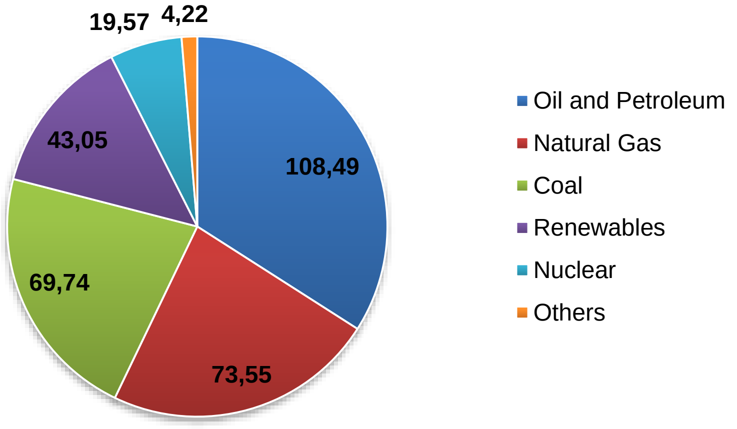
1.2.1 Primary Energy Mix

The Primary Energy Mix provides power to all economic activities that need an energy source that can be found in nature and which has not been converted by humans such as raw fuels. The primary energy market is formed by activities such as transportation, heating and generation of electricity.

The GIC measures the demand of energy of this mix as well as the total energy demand of a country, it is defined as the sum of the Primary Energy Production and the Net Energy Trade (plus the storage energy minus energy losses). In the case of Germany, when the Primary Energy Mix is quoted, the units of study will be always quoted to the GIC (in Mtoe) due to the large energy deficit that the country has got, it is more representative to refer to energy demanded than just energy production.

In the year 2018, the country´s main energy sources consisted on: Crude oil and petroleum products (35%), Natural gas (24%), Coal (22%), Renewables and biofuels (14%), Nuclear (6%) and others (1%) (Figure 1).

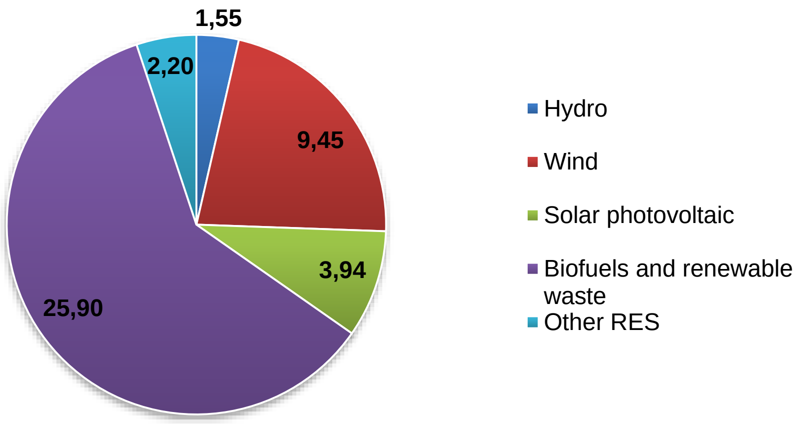
Figure 1. *Germany´s Gross Inland Consumption (2018) (in Mtoe)*



Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020)

Regarding the composition of RES that supplies the GIC, as it can be seen in Figure 2, it is made out of: Biofuels and Renewables Waste (60%), Wind (22%), Solar Photovoltaic (PV) (9.1%), Hydro (3.6%) and other RES (5.1%).

Figure 2. *Germany´s Gross Inland Consumption by RES (2018) (in Mtoe)*



Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020)

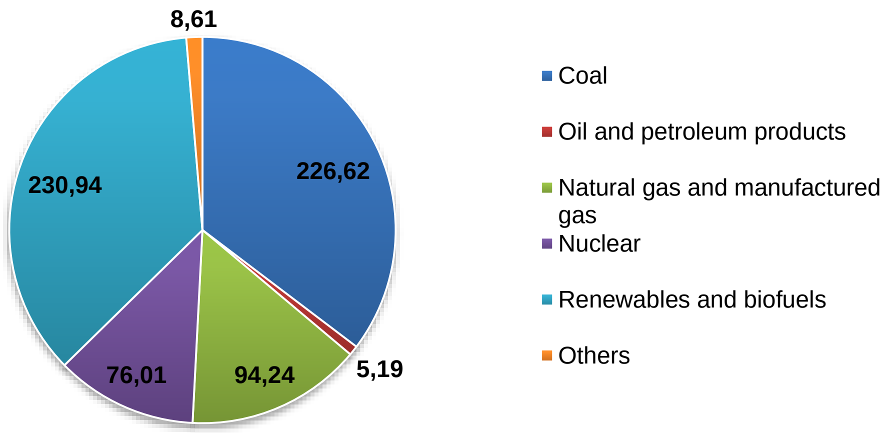
1.2.2 Electricity Mix

The Electricity mix caters all activities that use a converted product from a primary energy source, like electricity, to satisfy its power needs.

Germany is characterized for being a front runner in the use of RES within its electricity mix, being its principal energy source when producing power (if Biofuels are considered as RES).

The composition of the secondary energy mix according to the national electricity generation is for the year 2018 (Figure 3): Nuclear Renewables and biofuels (36%), Coal (35%), Natural and Manufactured gas (15%), Nuclear (11%) Oil and Petroleum Products (0.8%) and Others (1.3%).

Figure 3. *Germany´s Electricity Production (2018) (in TWh)*



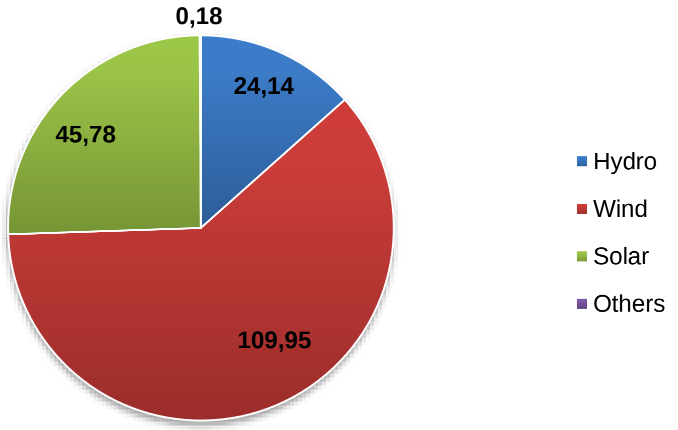
Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020)

1.2.2.1 Renewable Energy Sources in the Electricity Mix

RES are the biggest component of this section with a 78% of the “Renewables and Biofuels”, generating the 28% of total the electricity.

Within in the RES, Wind is the main energy source with a share of 61%, then Solar (25.5%) and Hydro (13.5%). The outstanding contribution of the wind generates the 17% of the mix electricity (Figure 4).

Figure 4. *Germany´s Electricity Produced by RES (2018) (in TWh)*



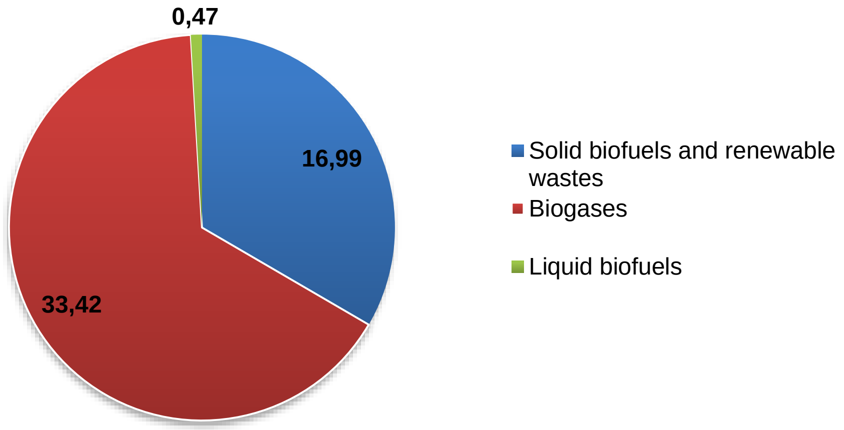
Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020)

1.2.2.2 Biofuels in the Electricity Mix

Biofuels generate the 22% of the electricity of the "Renewables and Biofuels", with a weight of 8% in the total Electricity production.

The largest contribution by far are the Biogases (66%), followed by Solid Biofuels (33%) and Renewables Wastes & Liquid Biofuels (1%<) (Figure 5).

Figure 5. *Germany´s Electricity Produced by Biofuels (2018) (in TWh)*



Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020)

1.3 Energy Sources

In order to fully understand the current composition of the German Energy Mix and its trend for the future (and therefore the background of the project), it is necessary to understand the main features of the most important conventional and RES, which are illustrated below. It is worth noting that some minor technologies such as geothermal wastes non-RES, Tide, Wave and Ocean are not included in this study due to its insignificance in the German Energy Sector.

1.3.1 Conventional Energy Sources:

Conventional Energy Sources supply 86% of the total energy demand and a 64% of the total electricity production. Despite the weight of this sort of energy sources in both mixes, due to established targets, regulations and future reduction of production costs of RES, this Conventional Sources are expected to be less important for the Energy Sector as time passes.

1.3.1.1 Nuclear

Germany´s Nuclear power future is as certain as non-existent; the country has maintained over the last years an anti-nuclear power policy due to political pressures to the current conservative government. As a matter of fact, 17 nuclear power plants have been already shut down and the 8 remaining are expected to be closed by 2022.

The year 2036 was the prior deadline for ceasing all nuclear power plants located in the country, however, due to the Fukushima accident this date has been advanced to 2022 (Traber & Kemfert, 2014).

As a result of this policy, the installed nuclear power capacity in Germany was 9.5 GigaWatts (GW) in 2018 while in 2011 was 20.4 GW. Also, a decreasing trend can be observed in the nuclear-powered electricity production, being 76 TWh (11.8% of the total electricity produced) generated for the year 2018 and 140 TWh for 2010 (22.3% of the total electricity produced).

1.3.1.2 Coal

Due to the long tradition of coal mining in Germany, this energy source is the principal fossil fuel used in the country. However, a change of trend can be observed in the last decades, the peak demand for this mineral happened in the last quarter of the 20th century and has been decreasing ever since. As at 2018, coal supplies the 22.2% (69.74 Mtoe) of the GIC and the 35.5% (228.16 TWh) of the electricity production.

Because it is such a polluting energy source, the national authorities have decided to endorse other greener energy sources (as it will be explained later) and to discourage the use coal for the production of heat and electricity (among other things), as a result of these policies, the German Commission on Growth, Structural Change and Employment has started the process shutting down the 38 coal-fired energy plants remaining in Germany by 2038.

Furthermore, the German Hard Coal is not a competitive resource in the international landscape anymore, so to meet a large part total coal demand, it is cheaper to import it from other countries.

In order to meet the 2050 and prior targets it seems certain that the phase out of coal powered plants is inevitable, unless a cheap technology to capture CO_2 is developed, that could potentially save thousands of jobs related to the sector. (Oei et al., 2020).

The carbon capture, utilization and storage (CCUS) technology is expected to boom within the next years, capturing 0.7 Gt of CO_2 emissions by 2030 and 2.8 Gt by 2050 (28% of the total expected CO_2 for 2050).

Nevertheless, one of the perks of running away from coal, as it happens with all fossil fuels, is the reduction of imports made by Germany.

When it comes varieties of Coal, they can be classified into two types: Brown Coal (or Lignite) and Hard Coal:

Brown Coal (or Lignite)

On the one hand, the Brown coal, which is highly polluting, is mined in the nation, setting the country as the biggest producer of Lignite worldwide thanks to its vast deposits. Thus, Germany does not have to import that much of this sort of coal.

The principal uses of the Brown Coal are heat generation and electricity production (among others) and used to supply the 11.5% of the GIC.

Hard Coal

On the other hand, the German Hard Coal is no longer competitive, and the fact that the Coal Subsidy ended back in 2018 pushed the country to import large amounts of this type of coal while producing virtually nothing of it.

The main suppliers of Hard Coal for the year 2019 are Russia (35 %), the United States (18%), Australia (13%) and Colombia (11%).

Hard coal accounts for the 10.6% of the German GIC, being used for the generation of heat and production electricity (as it happens to Lignite).

1.3.1.3 Gas

Germany is the 8th largest consumer and the biggest importer of gas in the world, only producing the 5% of the gas that the country consumes. In contrast to the rest of all non-environmentally friendly energy sources. The use of gas has gained weight both in relative and absolute terms in the electricity mix, the use of gas for electricity production has increased over the last years, shifting from 60 TWh (10.4% of the total electricity production) in the year 2000 to 94.2 TWh in the year 2019 (14.7% of the total electricity production).

The evolution of the use of gas in the energy sector is explained by the energy transition that the country is experiencing. The use of gas is a suitable exit from nuclear and other non-RES in the transition towards RES.

The principal uses of gas are the generation of electricity and heat, consumed primarily by the industrial sector and households.

One of the main drawbacks of the RES is that the power produced by them can only be stored in batteries, nowadays battery prices are still too high to store all the electricity surplus that the RES can produce in Germany, and it is needed in order to supply power when there is an energy shortage during peak energy demand circumstances. In contrast to traditional energy sources such as nuclear or coal can be turned on or off whenever they are required. Thereby, the use of a fossil or nuclear source is needed, and gas is the best candidate. First, it is one of the least polluting fossil fuels. Second, it is also affordable and cheap to store and transport. Therefore, gas is a good substitute in this transition while waiting for the further development of RES and the drop of battery prices (Wettengel, 2020).

Nevertheless, not everything in the use of gas is good. Gas is after all a fossil fuel and even though is more environmentally friendly than other fossil-powered energy sources, it still pollutes. In addition, the main countries from which Germany imports the gas it consumes are Russia (40%), Netherlands (29%) and Norway (21%). Being two of these countries outside of the EU, and one of them, Russia, is a country against the European Union Project and its Interest. Furthermore, all the gas imported from Russia comes through the Northern Lights and Yamal-Europe Pipeline which is partly located in Ukraine, a nation that has increased the transportation fees of the pipeline as a political response to Russia, and by doing so, the cost of gas importing has significantly increased. This unstable geopolitical situation is expected to be solved when the Nord Stream 2 Pipeline, a Pipeline that connects Russia and Germany through the Baltic Sea, is completed (Adomeit, 2016).

In conclusion, gas is an affordable and a greener alternative to the former energy production scheme, although it must be replaced by RES and batteries in the long-term.

1.3.1.4 Oil and Petroleum Products

As it happens with the Gas, Germany´s petroleum reserves are slim, having to import almost all of oil that the country consumes. In the year 2017, Germany´s imports of crude oil accounted for the 97.6% of the crude oil consumed, being Russia the country that exported most oil to Germany (33.5 million tonnes of crude oil accounting for the 37% of oil imports), next Norway with 10.3 million tonnes (11.4% of all imports) and United Kingdom with 8.5 million tones (9.4% of all oil imports) (among others).

The principal uses of oil are transportation and electricity production in a residual share.

Like all fossil fuels, Germany has got a strong dependence of imports of oil from non-EU countries. However, due to environmental concerns and the proliferation of non-fossil-powered transportation, the demand of oil and petroleum products imports are expected to fall in the next years.

1.3.2 Renewable Energy Sources and Biofuels

RES and Biofuels provide 38% of the total energy demand and a 36% of the total electricity production.

Since the first Renewable Energy Act was passed in the year 2000, the total energy output generated by Wind, Solar and Hydro is now 5.6 times more (as of 2018) and these sources combined now produce 5.1 times more electricity than in the base year. Even though RES still are minor energy sources in the Primary Energy Mix compared to solid fossil fuels, the sudden soar that the RES have experienced during the last years has been outstanding and it is expected to keep growing.

In the year 2018, 291,000 people were employed in the Renewable Energy Sector in Germany, being the largest renewable workforce in Europe and the 6th worldwide, representing the 1% of Germany´s Gross Domestic Product (GDP) (International Renewable Energy Agency, 2019).

1.3.2.1 Wind

Wind energy is the first RES, accounting for the 22% (9.5 Mtoe) of the energy consumed in the Primary Energy Mix generated by RES, and 62% (110 TWh) of the electricity production by RES with an installed capacity of 58.8GW for the year 2018.

There are two types of wind farms: Onshore Wind Farms, which are based on land, are cheaper to install, run and its transmission of electricity is inexpensive. And Offshore Wind Farms, that can be found on masses of water, usually oceans and are also a more stable and reliable energy source that can face higher wind speed, but are more capital-intensive compared to Onshore Wind Farms, being pricier to install, operate and transmit the energy to the mainland [Junginger et al. (2004) and Enevoldsen & Valentine (2016)].

<u>Onshore Wind</u>

Onshore is the most popular wind energy source in the country, with more than 29,000 onshore turbines installed in the year 2018.

In terms of power production and installed electricity capacity, more than 85% of them are attributed to the Onshore Wind in the total Wind production (IEA Wind TCP, 2019).

<u>Offshore Wind</u>

Offshore Wind turbines in the year 2018 surpassed the number of 1,500 turbines, most of which being in the German North Sea and Baltic Sea. And it only generates less than the 10% of the total electricity produced by wind.

The great difference between Offshore Wind and Onshore Wind regarding number of turbines installed, electricity production and installed electricity capacity is a consequence of the intrinsic characteristic of both wind energy production technologies such as price, space needed to place the turbines and distances from where it is produced to where the power is consumed.

1.3.2.2 Solar

As for Solar Energy Sources, they can be classified into two types: Solar Thermal and Solar PV.

Solar Thermal

Solar Thermal Sources capture the sun´s heat and transform it into mechanical energy that is later transformed into electricity, or the heat is sent directly to where is needed (such as heating systems) (U.S. Energy Information Administration, 2019).

However, Solar Thermal is a minor energy technology due to the lack of versatility of this energy source compared to the Solar PV, standing with only just the 0.24% of the energy demanded in the country as of 2018 (in terms of GIC).

Solar Photovoltaic

Solar PV Sources capture the sunlight and by using panels made of semiconductor cells convert it into electricity. (U.S. Energy Information Administration, 2020).

In the last years, Solar PV has experienced a huge boom in Germany thanks to the efforts of the legislator to encourage the use of this technology for household supply and for the creation and expansion of new Solar PV farms.

As a result of these policies, Germany has got more than 1.8 million solar arrays with a total installed capacity of 45.179 GW in the year 2018 (compared with to 114 GW in the year 2000), whereas the electricity production shifted from a 0.06 TWh production in the year 2000 to a 45.78 TWh electricity generation (7.1% of the power generated in the electricity mix) in the year 2018, a 76,300% increase in less than 20 years.

Nevertheless, the Achilles heel of the Solar PV and Thermal, as it happens to all RES, is that they are unable to support a regular production of electricity, having to rely on fossil fuels for supplements. But according to the *Bundesverband Solarwirtschaft* (German Solar Industry Association), the future reduction in battery prices for household energy storage will boost even more the use of Solar PV technology.

1.3.2.3 Biofuels

Biofuels are all-around energy sources, they are extracted from biomass (such as cellulose, animal wastes or lignin) and through one or several process like the Hydrolis, Fermentation or Photolysis a Biofuel (Biogases, Biodiesels, Bioethanol, among others) is obtained.

They are used for a large variety of things such as power generation, transportation and heating, being an affordable and green alternative, that can be used whenever they are needed. This could be a great a way of balancing out the electricity mix without using batteries or fossil fuels during peak electricity demand circumstances (Hansen et al., 2019). Due to all the advantages that the Biofuels have, 22% of the energy green electricity produced in the country was generated by Biofuels.

1.3.2.4 Hydro

Hydro is the 4th largest green energy source in Germany, accounting for the 11.8% of the energy produced by RES and Biofuels and for the 4% of the total electricity production in 2017, with a total installed capacity of 11,120 MW (more than the nuclear sources).

There are two sorts of Hydro Power installations: Gran Scale Hydropower plants and Mini-Hydropower plants.

Grand Scale Hydropower has got dams and large reservoirs that can store water for long periods of time, with the advantage of supplying power during peak demand hours. As it happens with Biofuels, this is an important feature in the green energy production in order to balance out the electricity mix when needed. Grand Scale Hydropower is the largest Hydro source, supplying the 77% of the electricity produced by these sources in 2017.

Mini-Hydropower plants are small-sized and simple facilities, which do not have dams or reservoirs, and are more environmentally friendly options because they do not interfere with the water flow and are a convenient energy source for remote locations. This technology only produces 23% of the electricity generated by hydro sources, however, because its simplicity they are cheaper to install and to operate than Grand Scale Hydropower plants (International Renewable Energy Agency, 2020).

1.4 Evolution of the German Energy Variables in the EU context

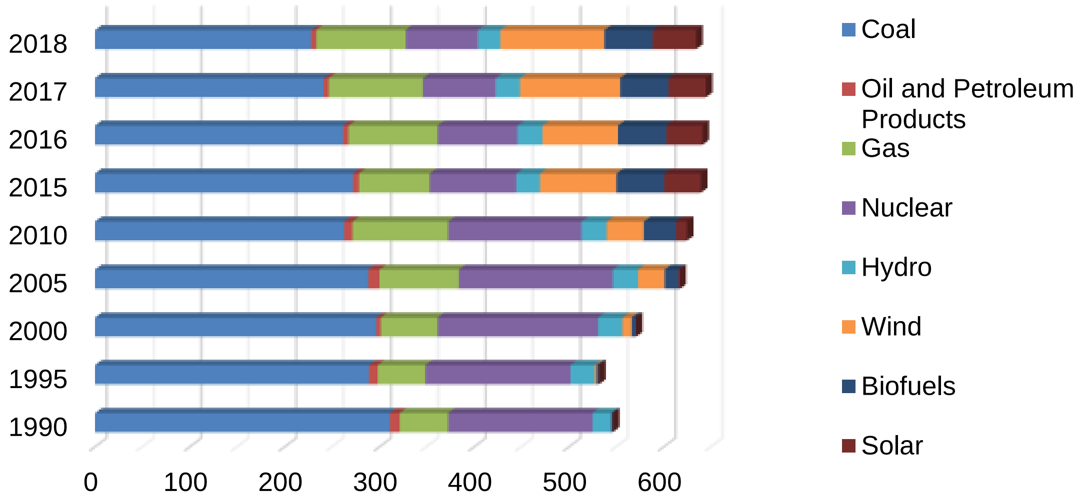
The comparison between the evolution of the German Energy Variables and the ones of the EU´s will give a firm perspective of what the role of Germany has been in the energy transition and the consequences of following this path.

1.4.1 Electricity Mix

As mentioned before, the proliferation of Germany´s RES has been outstanding in the last decades, especially since the beginning of the century when the first EEG was passed, which led to a greener energy production. As it can be observed in the Figure 6, almost all RES and Biofuels have increased significantly in the electricity production. Among the environmentally friendly sources, Hydro and Biofuels seems to be stuck in the amount of electricity produced yearly over the last decade, however, Solar (mainly PV) and Wind seem to be inexorable, growing at large rates since the year 2000.

Notwithstanding the importance of Conventional Energy Sources (predominantly Coal and Gas) for the electricity production is still large, however, the amount of electricity generated by them in last decades is downwards, being particularly remarkable the production cut of Nuclear Sources (as mentioned in the point 1.3.1.1 Nuclear). Nevertheless, Gas is the only fossil-powered energy source that has gained importance in the electricity production both in relative and absolute terms.

Figure 6. *Germany´s Electricity Mix Composition (1990-2018) (in TWh)*

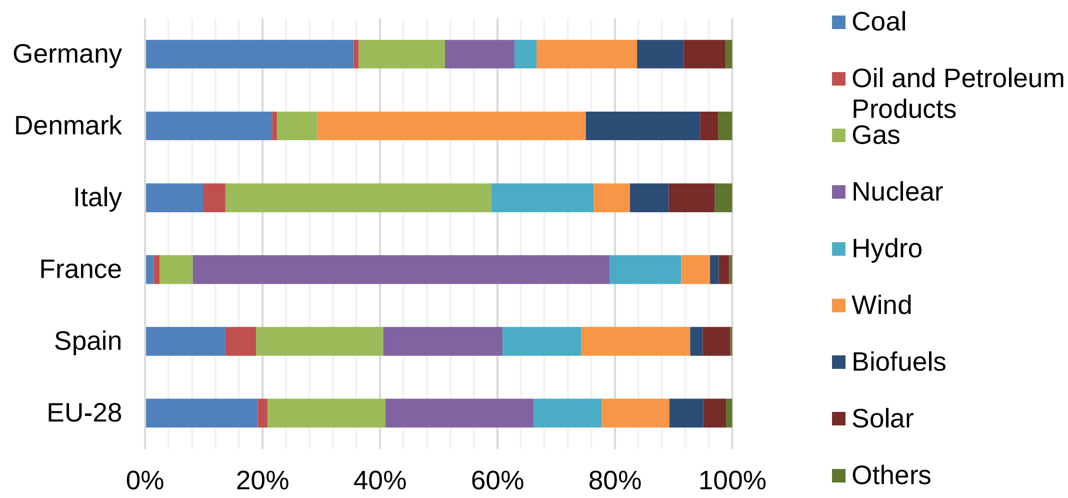


Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020)

Concerning other European nations, Germany´s green energy production is above the EU-28 average, nevertheless there are some countries that are much more advanced in this regard. Denmark is the best example, producing more than 70% of their electricity through RES and Biofuels. Even some major economies such as Spain or Italy are more settled in the environmentally friendly electricity production (Figure 7).

It is worth noting on which energy source each country relies. France has a strong dependence on Nuclear, having the cheapest household electricity price among the big economies of the EU (though emission cost and energy production risks are not internalized in this price). Italy heavily leans on gas due to the multiple gas pipelines that flows towards the country from locations as diverse as Russia, Azerbaijan, Libya or Algeria. Denmark has got a wide network of Wind farms across the country due to its geographical location and climatological features. And Germany, due to its large coal deposits and its long coal mining tradition still relies on this fossil fuel despite its transition towards a greener model.

Figure 7. *EU´s countries Electricity Mix (2018)*



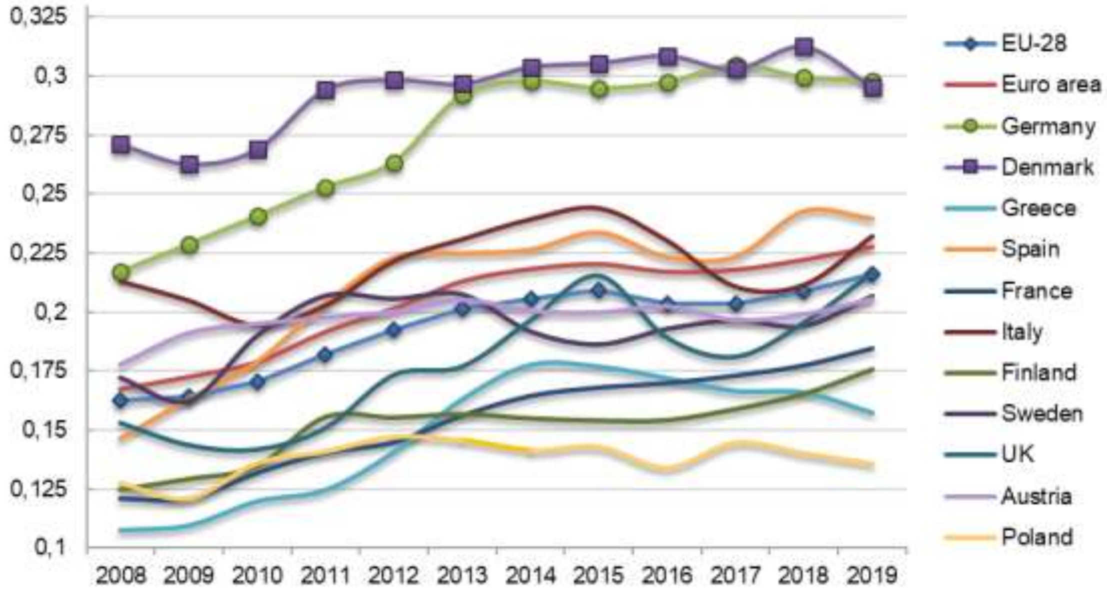
Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020)

1.4.2 Electricity Price

The electricity prices in Germany over the last decades have been the second highest in the EU after Denmark, in addition a sudden increase in the electricity prices has occurred in the last years because of the Nuclear phase-out and energy transition surcharge policies of the authorities.

Nominal electricity prices for the period 1998-2019 in Germany has increased by 78% (33% in real terms), above the average of the EU-28 (being the country with the biggest prices increase over the period 2008-2019 as seen in Figure 8, even though the EU has set ambitious goals in terms of renewable electricity production and regulation, the Germany´s determination of being a front runner in Green Energy Production and going beyond the European milestones has the consequence of this rise, being 53% of the electricity bills taxes and levies (which have been increased in a higher percentage than the inflation rate over the last years), part to subsidy the so called *Energiweinde* (Bode & Groscurth, 2006).

Figure 8. *Evolution of Germany´s Household Electricity Price (2008-2019) (in Euros/kWh)*



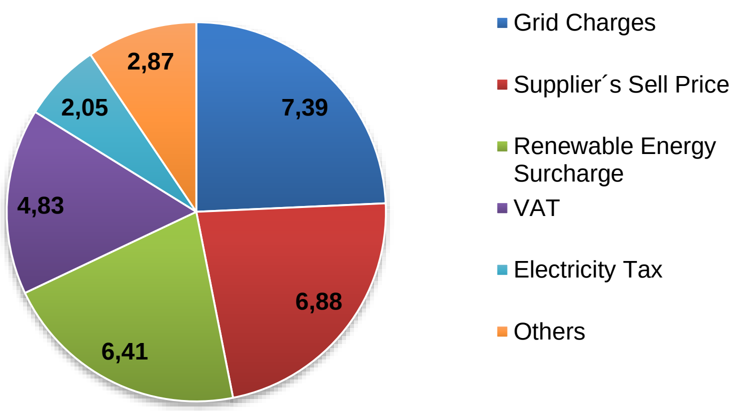
Source: Eurostat (2020).

The average price of household electricity in the consumption band 2,500 kWh-5,000 kWh in the year 2019 was 0.3043 Euros/kWh.

Most of the price charged (24%) comes from the grid cost at 0.0739 Euros/kWh, i.e. the fees of using the network to deliver the electricity, which is slightly more than the supplier's sale price of electricity (including its cost and markup) at 0.0709 Euros/kWh (23%). Renewable Energy Surcharge takes 21% of the price at 0.0641 Euros/kWh, which is used to subsidy the energy transition by offering long-term contracts to the renewable energy producers. The price also includes taxes paid to the government: Value Added Tax at 0.0486 Euros/kWh (16%) and Electricity Tax at 0.0205 Euros/kWh (7%). Other surcharges to finance the energy transition represents 9% of the price at a rate of 0.0287 Euros/kWh. (Figure 9).

However, it is worth noting how the difference between electricity prices and bills for households affects the energy transition. By contrast, German industry in general bears a less heavy burden in moving towards a more efficient way of power use, because a portion of the fees and surcharges is waived for part of the industry therefore it lacks the strong incentive as households.

Figure 9. *Germany´s Household Electricity Price Composition (2018) (in EuroCents/kWh)*

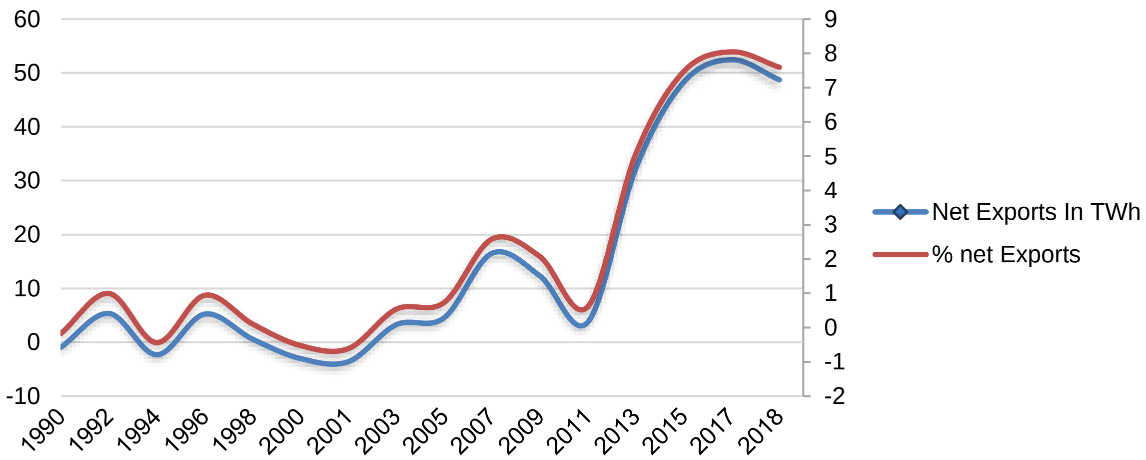


Source: Author´s own elaboration Employing Data from Bundesverband der Energie- und Wasserwirtschaft (2019)

1.4.3 Electricity Trade

The German electricity trade balance had no clear pattern prior to early 2000´s, nevertheless, from 2003 onwards a strong export trend can be observed, more than 8% of the total electricity production was exported in the year 2017 (Figure 10). This drift in the behavior of electricity trade balance coincided with the time when the first EEG was passed, which caused the country to heavily invest in RES. The current situation of national net exporter of net exporter is explained by the electricity surplus of RES during low demand/high production hours and the gains in energy efficiency which led the country to produce the same GDP output with less energy consumption as it will be explained in the next point.

Figure 10. *Evolution of Germany´s Electricity Trade Balance (1990-2018)*

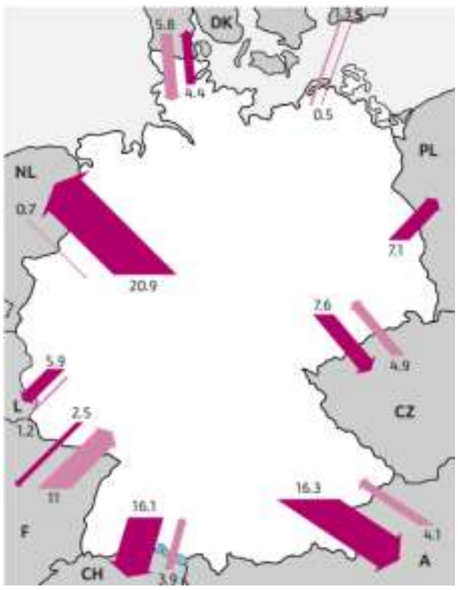


Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020)

As of 2017, Germany was a net electricity exporter to 6 of its neighboring countries and a net importer to the 3 remaining (Figure 11), being crucial for Netherlands´ and Switzerland´s electricity supply and the central hub for electricity exchange in Europe.

The more connected the EU countries are in terms of electricity grid, the more favorable will be for the production of it by RES, because by having access to a larger electricity market it is less likely that the power generated by RES in Germany during a electricity production surplus time has to be stored in batteries or wasted.

Figure 11. *Germany´s Electricity Trade with its Neighboring Countries (2018) (in TWh)*



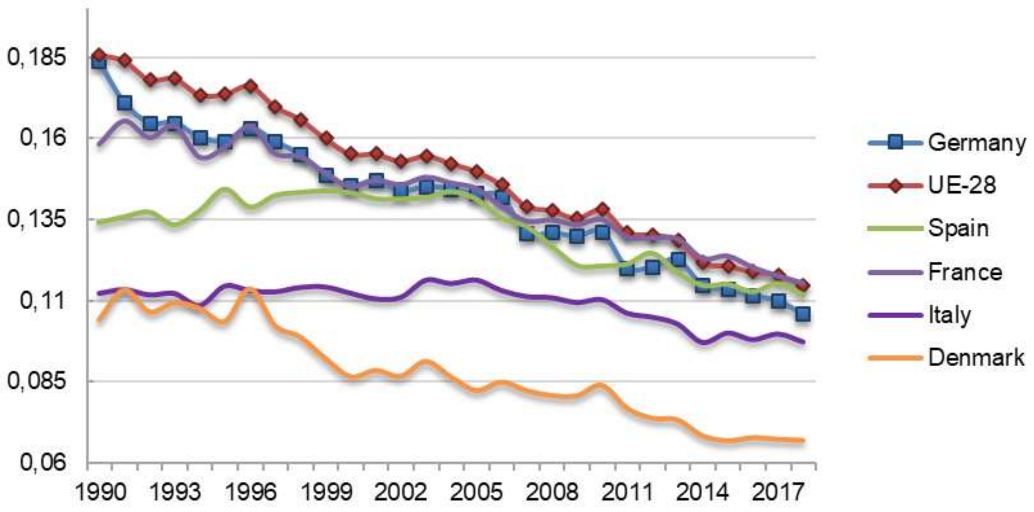
Source: Bundesverband- der Energie und Wasserwirtschaft (2019)

1.4.4 Energy Intensity

Energy intensity is defined as the ratio between the GIC and GDP, this relationship shows how efficiently a country uses the energy to generate wealth.

In the last decades, Germany´s Energy Intensity has been improved above the EU-28 average, and only a few countries such as Italy or Denmark (among others) are more advanced in this regard (Figure 12. .

Figure 12. *Germany´s Energy Intensity (1990-2018) (GIC/Real GDP 2010)*



Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020)

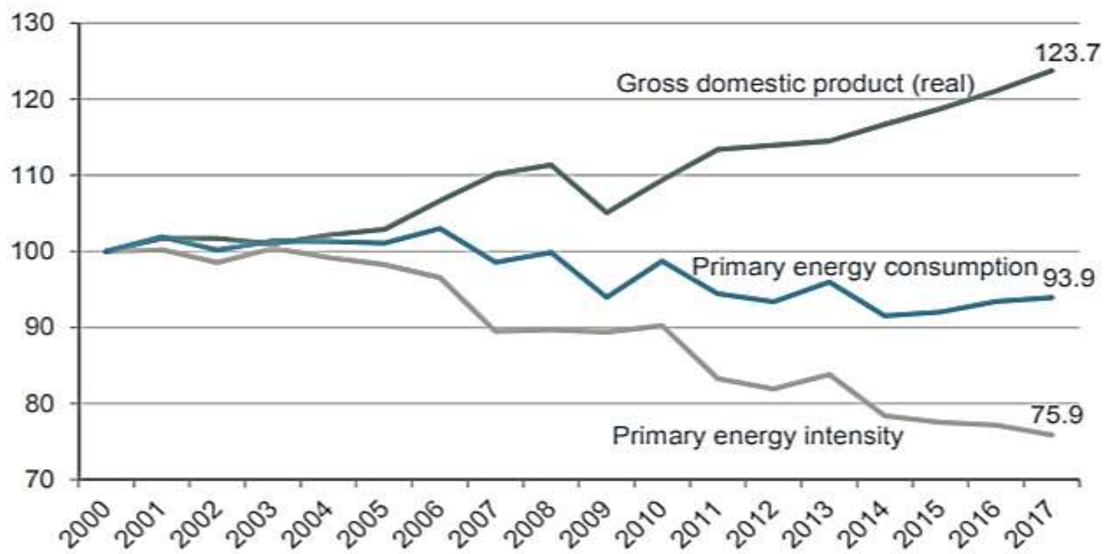
Due to all the environmental regulations to reduce Primary Energy Consumption by improving the energy savings of households and industry, high electricity prices and the increasing use of RES (that have a higher electrical conversion efficiency than conventional energy sources) in the electricity mix, has caused Germany to become one of the countries that consumes its energy most efficiently, the country both in the EU and worldwide (Brüggemann, 2018).

Other variable that measures the energy efficiency is the Primary Energy Intensity, which is the ratio of Primary Energy Consumption divided by the Real GDP. It is useful to study the evolution of how much non-electrical energy is needed to produce one unit of GDP, and, as the energy transition advances, the importance of the electricity in the GIC growths, being less and less important the Primary Energy Consumption, this ratio is also an indicator of the progression of the Energy Transition.

The decrease of the Primary Energy Consumption in order to meet the European aims of cutting 20% in 2020 the levels of that variable, is a clear explanation of why the Primary Energy Intensity has increased so much over the last years, however, it is not likely that this goals are going to be met by that deadline (Figure 13).

The current target for 2030 is to reduce the GIC by 30% and for 2050 by 50% compared with it in 2008, whereas the Gross Electricity Consumption is expected to be 25% lower than in the base year 2008. These objectives are expected to be achieved through an aggressive cut in Primary Energy Demand of Buildings (80% less than in 2008), Final Energy Consumption transport (40% less than in 2005) and Heat Demand of Buildings (20% less than in 2008) by the year 2050, reaching a 2.1% increase in Energy Intensity every year until 2050. (Federal Ministry for Economic Affairs and Energy, 2017).

Figure 13. *Evolution of Germany´s GDP, Primary Energy Consumption and Primary Energy Intensity (2000-2010) (Base 2000=100)*



Source: Brüggemann (2018)

2. National and European Regulatory Framework

In order to fully understand the current situation in the German Energy Sector and its targets for the future we must review the main pieces of legislation passed at a national and European level.

2.1 German Renewable Energy Sources Act

The EEG is a series of German laws that enable the energy supply to develop in a sustainable way, mitigating climate change and protecting the environment, reducing the costs of the energy supply to the economy including long-term external effects, conserving fossil energy resources and promoting the further development of technologies to generate electricity from RES.

The first EEG was passed in the year 2000 with the purpose of boosting the generation of electricity from RES, doubling the share of electricity produced from renewable energy by 2010. A guaranteed feed-in tariff scheme provided finance to the green energy producers through 20-year electricity production contracts which offer a cost-based compensation, providing price certainty that helps finance renewable energy investment and a 5% to 10% profit margin depending on the RES. This structure was financed through a surcharge to the energy consumer and industries (as seen in the point 1.4.2 Electricity Price of the study) with no charge to the German Public Finance. Furthermore, not only the electricity production is encouraged by the EEG (2000), also the consumption of it, the grid operator is required to prioritize the delivery of electricity produced by RES rather than Conventional Energy Sources.

Finally, the EEG (2000) enhanced the innovation of the RES by providing decreasing feed-in tariffs at regular intervals that pushed the energy producers to become more cost-efficient as time passes. The regulator focused on setting bigger incentives on PV and wind, as they were promising energy sources that were expected to improve outstandingly over the other sources.

After the EEG (2000) several Renewable Energy Sources Act and Photovoltaic Acts were passed, however the Renewable Energy Source Act (2014) was especially noteworthy for changing the feed-in tariff scheme and replacing it with an auction structure instead of long-term contracts, paying the electricity producers the difference between the bids in the auctions and spot prices of electricity, so they can always receive the spot prices. Moreover, this EEG specified the scope to which the RES will be expanded in the next years by setting growth corridors, or limits on the number of new green energy installations.

As a result of the EEG passed in 2000, the share of Renewable Energy (including biofuels) in the GIC has increased from 2.6% to 13.7% by the year 2018, and regarding the weight of RES (including biofuels) in the Electricity Production from 6.9% in 2000 to 36% in the year 2018. (Lang & Lang, 2015).

However, this growth has been even more remarkable for energy sources that the EEG gave a leader role in the energy transition such as the Wind (both offshore and onshore) and Solar PV (as it was commented in the points 1.3.2.1 Wind and 1.3.2.2 Solar) (Auer & Anatolis, 2014).

In addition, the way of producing and distributing electricity has changed: Due to the incorporation of new green technologies such as the Solar PV arrays that can be installed in the household at an affordable price, the country has shifted from a centralized fossil fuel-based production model to a green decentralized one, that has lowered the electricity price during high demand hours. However, the general price of electricity (excluding peak demand circumstances) is now higher because of the levies such as the feed-in tariffs and other mechanisms to finance the energy transition.

Lastly, the EEG had also a positive impact on the jobs created in the Renewable Energy Sector. In 2018, 291,000 workers were employed in the sector, and two thirds of these job positions existed thanks to the EEG.

2.2 European Green Paper

The European Green Paper (Commission of the European Communities, 2006) is a discussion document, released in 2006 by the European Commission, which set the European Energy Policy for the next 20 years to develop a fully competitive, interconnected and environmentally friendly internal energy market through a common response of all EU members and to tackle the threats in the EU sustainable energy project such as: dependency on energy imports, volatile oil and gas prices, energy efficiency and climate change.

The Green Paper (as well as the European Green Deal) is not a set of regulations *perse,* but many policy proposals on the same topic yet remaining uncommitted. Nevertheless, the European Green Paper has been the reference for the European Energy Transition from 2006 to the next decade, also being the forerunner for many legislative initiatives such as the European Green Deal that defines the present and future the Energy Policy in Europe.

The paper sets six priority areas for the implementation of the European Energy Policy:

1. <u>Energy for growth and jobs in Europe: completing the internal European electricity and gas markets</u>

   Many European Countries still have protectionist energy markets with a few companies having almost all the share. In order to have a competitive market and to secure the energy supply it is necessary to improve the energy infrastructure connecting the EU countries and its philosophies

   - European Grid with common rules and standards, giving the possibility of selling energy to other countries in the same conditions as the national producer.
   - Priority interconnection plan: Boost the investment in infrastructure involving different national grids.
   - Investment in generation capacity: To solve the problem of suppling energy to peak demand hours.
   - Improving the competitiveness of European Industry by having lower prices.

- A level-playing field: the importance of unbundling.

2. An Internal Energy Market that guarantees security of supply: solidarity between Member States

Due to Europe´s large energy dependency on imports, it is necessary to secure the energy supply by creating energy reserves, by setting up a European Energy Supply Observatory that monitors potential energy shortfalls and by stablishing a solidarity mechanism which allows the countries to supply energy to other member states in case of shortage.

3. Tackling security and competitiveness of energy supply: towards a more sustainable, efficient and diverse energy mix

The composition of each country´s energy mix should be agreed upon with the rest of EU members, evaluating the impacts on sustainability, competitiveness and security of energy in the EU.

4. An integrated approach to tackling climate change

The main goal of this point is to make the economic growth uncorrelated with the energy consumption, advancing towards a more energy efficient scheme as well as to a more environmentally friendly way of producing energy.

5. Encouraging innovation: a strategic European energy technology plan

The innovation in Europe is the key element for security of supply, sustainability and competitiveness. Therefore, the European Commission seeks a more efficient way of producing and consuming energy through a strategic energy technology plan.

6. Towards a coherent external energy policy

An external energy policy must enable the EU to respond with one voice to the energy challenges of the coming years while enhancing the relationships with EU´s energy partners such as Russia.

2.3 European Green Deal

The European Green Deal is a compilation of initiatives made by the European Commission released in 2020, that set the basis for the EU´s new growth and development model until the year 2050.

The main target of this Deal is to become climate neutral by 2050, meaning the pollution emitted from EU countries is absorbed by the atmosphere, having a net zero effect in the environment.

By achieving this goal, the EU could slow down or even stop climate change, stop the rising temperatures, preserve its biodiversity, decrease the pollution in its territory and improving its citizens health is the core motivation of these policies.

As it happens with the European Green Paper, these targets are expected to be achieved through eight-policy area changes.

1. <u>Increasing the EU’s climate ambition for 2030 and 2050</u>

The European Commission has passed the European Climate Law, which gives certainty for investors and guarantees that the energy transition is irreversible, furthermore, through an effective carbon pricing it is expected to change consumer´s and business´ behavior and to encourage public and private sustainable investments.

It also has stablished a new target for GHG emissions, to be reduced at least by 50% by 2030 and by 55% by 2050, compared with 1990 levels.

2. <u>Supplying clean, affordable and secure energy</u>

The decarbonization transition must be done with the least cost possible, providing a competitive, secure and clean energy. Also, there are plans to improve the electricity infrastructure. Finally, the risk of energy poverty must be addressed through grants to help households that cannot afford the power they consume.

3. Mobilizing industry for a clean and circular economy

The EU Commission knows that the energy transition is an excellent opportunity to expand the sustainable and job-intensive economic activity, thus the EU will make a new EU industrial strategy that combined with a new circular economy will modernize EU´s economy.
The circular economy plan aims to encourage businesses to offer reusable, durable and repairable products to their customers, and by doing so, waste will be significantly reduced.

4. Building and renovating in an energy and resource efficient way

Energy efficiency savings are crucial for using electricity in a sustainable and more productive way, as a key element of the energy transition, member states will encourage the massive renovation of public and private buildings.

5. Accelerating the shift to sustainable and smart mobility

Being transport one of the most polluting sectors of the economy, its emissions should be cut drastically, and due to the effects that it has on the environment and heath, these spillovers must be reflected in the transportation price.

Moreover, a cleaner way of mobility must be achieved using sustainable use of alternative transport fuels and vehicles. Finally, all fossil fuel subsidies must end.

6. From ‘Farm to Fork‘: designing a fair, healthy and environmentally-friendly food system

The Farm to Fork Strategy is also part of achieving the circular economy, by cutting down the environmentally harmful elements use in the production of distribution of food (such as chemicals, packaging or transport) the consumer and the environment can enjoy food with higher value and sustainability that meets all the quality standards.

7. Preserving and restoring ecosystems and biodiversity

With the purpose of preserving Europe´s wide biodiversity, the Commission wants all economic activities not to be a threat for the environment. Additionally, large investment will be made to preserve the oceans, forests and species of the continent.

8. A zero pollution ambition for a toxic-free environment

   The European Commission will adopt in 2021 a zero pollution action plan for air water and soil, will review the measures to deal with the pollution of large industrial installations and will present a chemicals strategy for sustainability.

   The global challenges of climate change and environmental degradation require a global response rather than that EU tackles this issue on its own. (European Commission, 2019).

Furthermore, there are many externalities of this Green Deal such as being a reference for emerging economies for a sustainable economic growth, boosting new areas of innovation or improving public health. It is estimated that 3.6 million premature deaths happen annually worldwide (430,000 in the EU) as a consequence of not replacing fossil fuels by RES in sectors like energy, transport, housing, food, industry and health. (Haines & Scheelbeek, 2020).

3. New energy consumption scheme and SARS-CoV-2

The current energy transition happening in Germany since the beginning of the century, which is characterized by the electrification of the total energy produced and consumed in a country, by the increasing weight of RES in the power generation and by the decreasing energy consumption through energy efficiency gains in transportation, households and industries, seems to be unstoppable worldwide (especially among developed economies).

Furthermore, the *Severe Acute Respiratory Syndrome Coronavirus 2* (SARS-CoV-2) outbreak has been a catalysator for this energy transition. The global electricity production during the first quarter of 2020 shrunk by 2.6% compared to the first quarter of the previous year, also the electricity demand has plummeted, opening a path for the Renewable-based electricity production, which is now 3% larger than in Q1 of 2019.

Most of the RES production depends on the climatological conditions such as sunlight or wind, nevertheless, Conventional Energy Sources are run (or not) by the will of the grid operators. These facts explain the rise of RES in the power generation, when a severe energy demand slump occurs, less electricity is needed, hence less Power from Conventional Energy Sources is produced. As a matter of fact, during the first quarter of 2020, 8% less electricity from coal, 4% from gas and 3% from nuclear was supplied to the market. Notwithstanding, the power production from sources such as wind or Solar PV has risen steeply with a more than 10% increase for each energy source.

Nonetheless, this quick change in the energy scheme does not only affect the amount of electricity consumed and supplied and how it is generated, but also the way that society uses and consumes it. Because of the lockdown the telecommuting was the leading way of office job among the most infected countries and it seems that it will be quite popular in the future too (even when all restrictions are lifted). The fact that the workers can do their jobs from home is a game-changer for the way that energy is used. First, the transportation (both private and public) is less used because there is no need to go the physical workplace. Second, less offices, factories and shop facilities are needed, so less energy is consumed by the agents that run them. And finally, because part of firm’s energy consumption is deflected to households, the property owners and tenants will now have an even bigger incentive to implement energy saving measures in their homes.

The SARS-CoV-2 outbreak had also a positive impact on the CO_2 emissions in the first quarter of 2019, being reduced by 5% worldwide, a larger percentage than the cut in electricity production.

Regarding the recovery of the economic activity and its consequences in the energy market, the lower the recovery is, the more beneficial will be for the proliferation of RES in the Primary Energy Mix and the Electricity Mix. To balance out the energy mix during peak demand hours with less dependence on Conventional Energy Sources will push the phasing out of coal, gas and nuclear power plants. According to the IEA projections for the year 2020, a V-shaped recovery will boost the production of power through both RES and Conventional Energy Sources, a U-shaped recovery will also boost the power production, but more from the RES, and a L-shaped recovery will boost tremendously the RES based power production (International Energy Agency, 2020).

This epidemic can be also a great opportunity for boosting the investments in low-carbon technologies by using the legislator´s stimulus packages and for meeting all the green energy production and pollution goals set in the Paris Agreement and the Green Paper and therefore improving public health (Steffen et al., 2020).

4. Markowitz´s Model and its application in the Energy Planning

Choosing how the electricity will be produced over the medium and long term in a country is a problem of investment selection and a major consideration in today’s energy and environmental planning. This decision must be made aiming for the least cost (economic and social), a substantiable production, minimizing the dependence on external resources, reducing air pollution, diversifying production among Conventional and RES, meeting the regulator´s agenda taking into account the life expectancy and the future electricity production of each energy source and granting the energy security to the nation.

Notwithstanding, selecting one portfolio between infinite investment possibilities that has got an unpredictable behavior is too risky and uncertain, hence Modern Portfolio Theory can lead country to pick the best option when it comes to producing electricity.

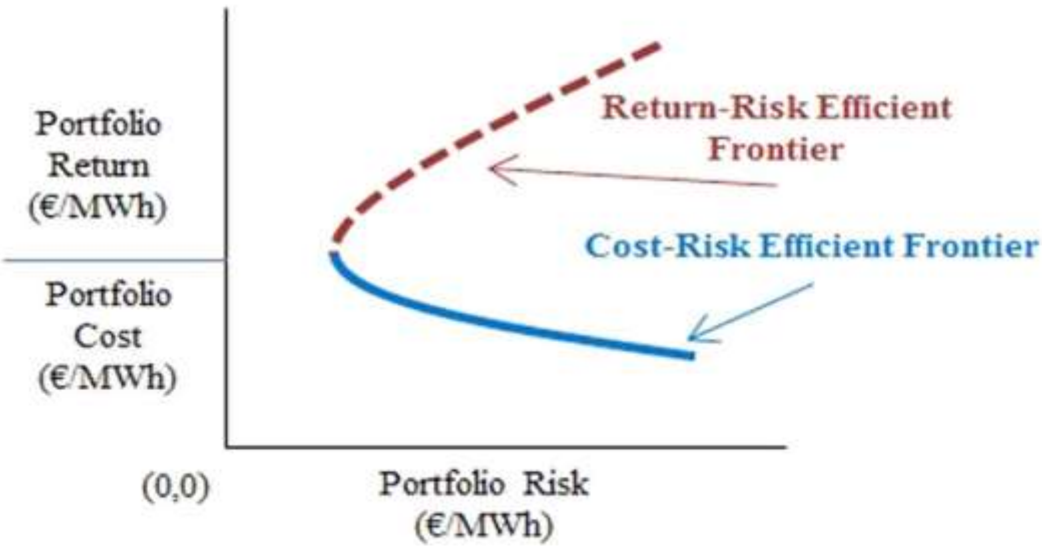
4.1 Modern Portfolio Theory

Modern Portfolio Theory (1952) was originally conceived to make the most efficient portfolio in terms of expected portfolio cost and expected portfolio risk regarding financial investments. The outcome of Markowitz´s approach is the so-called Efficient Portfolio Frontier, a range of portfolios that offer the best risk to return or the best risk to cost possible. It makes the investment selection much easier; the investor will only consider the portfolios located in the Efficient Frontier instead of endless investment possibilities.

Portfolio theory is highly suited regarding energy planning. Selecting the right way of producing electricity is comparable to investing in financial securities, managing the risk and maximizing the return under a set of unpredictable outcomes. Likewise, individual technology cost and return are not the key issues, instead, the total portfolio cost and portfolio return are truly important.

Along the Efficient Portfolio Frontier, some alternatives may have better returns while others may have tinier risks. But all combinations are considered to have the most optimal return-risk and cost-risk relationships (Awerbuch & Berger, 2003). As seen in Figure 14, when it comes to risk to cost, the upper part of the frontier gathers the more secure or stable portfolios while the lower section offers more potentially profitable investment portfolios.

Figure 14. *Risk to Return and Cost to Risk Efficient Frontiers*



Source: DeLlano-Paz et al. (2017)

Several authors [Awerbuch et al. (2009), Rodoulis (2010), DeLlano et al. (2015), Marrero et al. (2015) and Awerbuch & Yang (2007)] have applied the Cost-Risk analysis for different purposes, they have opted to define models based on the costs of the technologies and the risks associated with them. Hence, the Efficient Portfolio Frontier the authors had generated is cost-risk focus.

Moreover, a series of variables, such as the maximum price or the maximum share of each energy technology, will be restricting the model to meet all the goals mentioned in the previous point, the consequences of which will be a change in the composition and shape of the Efficient Portfolio Frontiers

4.1.1 Expected Portfolio Cost

The Expected Portfolio Cost is defined as the sum of the yields of all the assets of the portfolio.

In terms of Modern Portfolio Theory applied to electricity production, the yield of an asset is given by the inverse of the electricity generation cost, measured in monetary units spent per unit of power generated.

Expected portfolio cost is the weighted average of the individual expected generating cost for *n* energy sources:

$$EPC = X_1 E(LCOE_1) + X_2 E(LCOE_2) + \cdots + X_t E(LCOE_n)$$

- $X_1, X_2 \ldots X_t$ = *Fractional shares of the energy technologies in the electricity mix*
- $E(LCOE_1),\ E(LCOE_2) \ldots\ E(LCOE_n)$ = *Expected levelized costs of energy per MWh*

4.1.1.1 Levelized Cost of Electricity

The Levelized Cost of Electricity (LCOE) is the ratio of the total lifetime expenses versus the total electricity output measured in monetary units of a given energy asset, in terms of Present Value.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{Inv_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Elect_t}{(1+r)^t}}$$

- Inv_t = *Investment Expenditures including financing in the year t*
- $O\&M_t$ = *Operations and Maintenance Expenditures in the year t*

- F_t *= Fuel Expenditures in the year t*
- $Elect_t$ *= Electricity Generation in the year t*
- *r = Discount Rate*
- *n = Life of the system*

The expenses that the LCOE includes are the Investment Expenditures of the energy assets (including the interest paid each year if the investment is financed through a line of credit), Operations and Maintenance Expenditures, the expenses that the technology must carry out in its production, Fuel Expenditures, how much fuel the energy source use to generate electricity over its lifepath, and additionally, this formula might include CO_2 emissions as an expense since CO_2 emission rights are not free in the EU.

4.1.2 Expected Portfolio Risk

Expected portfolio risk in the electricity mix, is the expected year-to-year variation in the Levelized Cost of Electricity. It is also the weighted average of each individual technology Levelized Cost Variances, affected by their expenses´ correlation coefficients:

Expected portfolio risk (for a 2-period time frame)

$$EPR = \sigma_p = X_1^2\sigma_1^2 + X_2^2\sigma_2^2 + 2\, X_1\, X_2\, \rho_{12}\, \sigma_1\, \sigma_2$$

- X_1 & X_2 *= Fractional Shares of each technology in the portfolio*
- σ_1 & σ_2 *= LCOE ´s Standard Deviations of technologies 1 and 2*
- ρ_{12} *= Correlation Coefficient of O&M and Fuel Expenses of technologies 1 and 2*

The Standard Deviations of the LCOE are crucial to determine the level of risk that an electricity asset has got, because it measures how volatile the electricity production costs are: the more they fluctuate, the more uncertain it is to produce with this energy source, and therefore, riskier.

The Correlation Coefficients, ρ, measures the relationship between Operation & Maintenance Expenses of different energy sources as well as the co-movements of Fuel Expenses among technologies. Moreover, it is a measure of diversity, a lower ρ among portfolio components creates greater diversity, which reduces portfolio risk. For example, fuel-powered sources are strongly corelated in their expenses, so having a balanced portfolio using RES and Conventional Energy Sources will reduce the overall portfolio risk (Awerbuch & Yang, 2007).

4.2 Germany´s Efficient Portfolio Frontier Forecast

The main objective of this thesis is to make an accurate and realistic forecast about how electricity will be produced in Germany by 2030, 2040, and 2050. In order to make this estimation, Modern Portfolio Theory will be used.

Understanding how the electricity mix will look like is relevant when it comes to understand what will be the leading technologies for the next years, how much will it cost to produce power, what will be the expected investment trends among the different technologies and what will be the impact that electricity generation has on public health. Moreover, due to the front runner position of Germany as the biggest energy market in Europe and for its vast energy innovation, the outcome of this model is going to be also relatable to the path that the EU will follow for the next decades.

Following the aforementioned principles of Awerbuch, Yang, Rodoulis and DeLlano-Paz, the model´s forecast will be obtained through the next formula:

Objective function:

$$Min\ \{\sigma_p\}$$

Subject to:

$$E(C_p) = C$$

$$X_n \leq \ Maximun\ Fractional\ Share\ of\ each\ technology\ n;\ \forall n$$

$$\sum_N X_n = 1 \in N{:}\ X_n\ \geq 0$$

4.2.1 Markowitz´s Model Data

The following data will be employed to make the Efficient Portfolio Frontier Forecast of Germany:

4.2.1.1 Levelized Cost of Electricity

Europe’s LCOE for the 2020-2050 horizon, as seen in Table 1, will be assumed to be the same as the German ones because no data was found forecasting the expected future LCOE of the country.

Also, they do not include the effects of CO_2 pricing, making the fossil energy sources more competitive than that they actually are. The LCOE data of the EU reference Scenario 2016 made by the European Commission does not consider this effect and the CO_2 emission fees for such a distant time frame are still unknown, so it is impossible to consider its consequences in this thesis.

Table 1. *Europe´s LCOE 2020-2050 (in Euros/MWh)*

	2020	2030	2040	2050
Coal	58.19	60.10	61.65	63.47
Gas	84.00	91.00	95.00	97.00
Grand Scale Hydropower	135.00	135.00	135.00	135.00
Mini-Hydropower	108.00	106.00	104.00	101.00
Onshore Wind	89.00	80.00	75.00	72.00
Offshore wind	123.00	105.00	95.00	90.00
Solar Center and North of Europe	108.00	95.00	89.00	84.00

Source: European Commission (2016)

The LCOE of Coal is calculated as the weighted average of Lignite and Hard Coal in the electricity production in Germany for the year 2018, being 36.44% Hard Coal and 63.56% Lignite.

All data is collected from the EU reference Scenario 2016 made by the European Commission except for Biofuels (International Renewable Energy Agency, 2012), which states that the LCOE for the year 2012 is 96.58 Euros/MWh, and since no projection of this variable was found in the elaboration of this thesis, no change from the 2012 observation will be assumed for the 2020-2050 horizon.

4.2.1.2 LCOE Variances and Standard Deviations

Using the LCOE mentioned above, Variances and Standard Deviations have been calculated for each energy sources (Table 2).

***Table 2**. Germany´s LCOE Variance and LCOE Standard Deviations 2020-2050 (in Euros/MWh)*

	Variances	Standard Deviations
Coal	5.06	2.25
Gas	32.92	5.74
Grand Scale Hydropower	0.00	0.00
Mini-Hydropower	8.92	2.99
Onshore Wind	55.33	7.44
Offshore wind	212.25	14.57
Solar Center and North of Europe	107.33	10.36

Source: Author´s own elaboration employing Data from European Commission (2016)

4.2.1.3 Correlation Coefficients

In order to measure part of the co-movements of the LCOE aforementioned, the covariances of Operation & Maintenance Expenses (Table 3) and Fuel Expenses (Table 4) for each energy source will be used.

Table 3. *Operation & Maintenance Correlation Coeficients by energy source*

	Coal	Gas	Onshore Wind	Grand Scale Hydro	Mini-Hydro	Offshore Wind	Biofuels	Solar
Coal	1	0.25	-0.22	0.03	0.03	-0.22	0.18	-0.39
Gas	0.25	1	0	-0.04	-0.04	0	0.32	0.05
Onshore Wind	-0.22	0	1	0.29	0.29	1	-0.18	0.05
Grand Scale Hydro	0.03	-0.04	0.29	1	1	0.29	-0.18	0.3
Mini-Hydro	0.03	-0.04	0.29	1	1	0.29	-0.18	0.3
Offshore Wind	-0.22	0	1	0.29	0.29	1	-0.18	0.05
Biofuels	0.18	0.32	-0.18	-0.18	-0.18	-0.18	1	0.25
Solar	-0.39	0.05	0.05	0.3	0.3	0.05	0.25	1

Source: DeLlano-Paz (2015)

Table 4. *Fuel Correlation Coeficients by energy source*

	Coal	Gas	Biofuels
Coal	1	0.92	-0.53
Gas	0.92	1	-0.15
Biofuels	-0.53	-0.15	1

Source: DeLlano-Paz (2015)

4.2.1.4 Health Index

Every year thousands of people die prematurely and suffer from severe and minor illness caused by air pollution, the forecast also aims to represent the spillovers of transitioning towards a RES based production scheme.

According to Markandya & Wilkinson (2007), the deaths, serious and minor illness caused by electricity generation per TWh by energy source in Europe are the following (Table 5):

Table 5. *Health effects of electricity generation in Europe by energy source (Cases/TWh)*

	Deaths	Serious Illness	Minor Illness
Hard Coal	24.5	225	13288
Lignite	32.6	298	17676
Oil & Petroleum Products	18.4	161	9551
Gas	2.8	30	703
Nuclear	0.052	0.22	0
Biomass	4.63	43	2276

Source: Markandya & Wilkinson (2007)

Thus, according to the European Commission data of electricity production by polluting energy sources, the health effects in Germany for the year 2018 were (Table 6):

Table 6. *Electricity produced by polluting energy source in Germany (2018) (in TWh)*

Hard Coal	82.57
Lignite	144.05
Oil & Petroleum Products	5.19
Gas	94.24
Nuclear	76.01
Biofuels	50.88

Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020)

And taking these generation values and multiplying them to the cases per TWh stated in the Table 5. Health effects of electricity generation in Europe by energy source (Cases/TWh), we get the deaths, serious illness and minor illness of the electricity production in Germany in 2018 (Table 7):

Table 7. *Air pollution effects by electricity source in Germany (2018)*

	Deaths	Serious Illness	Minor Illness
Hard Coal	2,022.97	18,578.25	1,097,190.16
Lignite	2,691.78	24,605.86	1,459,507.32
Oil & Petroleum Products	1,519.29	13,293.77	788,626.07
Gas	231.20	2,477.10	58,046.71
Nuclear	4.29	18.17	0.00
Biofuels	382.30	3,550.51	187,929.32
TOTAL	6,851.82	62,523.66	3,591,299.58

Source: Author´s own elaboration employing Data from Markandya & Wilkinson (2007).

4.3 Constraints

In order to make a realistic forecast, several constraints must be used to meet all the regulations and efficiency targets.

4.3.1 Energy mix´s composition

To have a diversified, realistic and environmentally friendly electricity, thresholds must be used as in the maximum share that a portfolio can use for a specific energy technology. By doing so, the model is not depending mainly on an energy source, and therefore, the risk associated with that sources (such as lack of wind in the case of windmill powered energy sources, systematic risk…) is spreaded among all technologies.

- Nuclear power will be limited to 0% due to the firm phasing out policy that the German legislator has carried out during the last decades and the announced cease of all nuclear power plants in the country by 2022.
- Due to its minor role in the power production (especially for the next decades) the model will not include Oil & Petroleum Products.
- In order to achieve the goals stated in the German Climate Action Programme 2030 (Clean Energy Wire, 2019) the weight of RES must be at least of 65% for the years 2030 and 2040, and 80% for 2050.

- Among the Conventional Energy Sources each technology will have the weight forecasted in the EU Reference Scenario 2016, e.g. In the case of Gas the EU Reference Scenario 2016 predicts a weight of 18.63% in the total electricity mix, but in order to meet the German Climate Action Programme 2030 targets, the maximum weight of coal for 2030 will be 11.18% (being the 18.63% of the power generated by Conventional Energy Sources).
- RES have the same thresholds of Conventional Energy Sources but with the difference that the maximum production limit is 100% larger than it would be if it was a fossil fuel source.

The model´s thresholds are compiled in Table 8:

***Table 8**. Germany´s maximum electricity generation share by energy source (2030-2050)*

	2030	2040	2050
Coal	23.82%	17.82%	10.47%
Oil & Petroleum Products	0%	0%	0%
Gas	11.18%	17.18%	9.53%
Nuclear	0%	0%	0%
Grand Scale Hydropower	8.96%	9.19%	9.83%
Mini-Hydropower	2.68%	2.75%	2.94%
Biofuels	26.09%	29.57%	31.15%
Onshore Wind	50.16%	48.51%	65.19%
Offshore wind	12.54%	12.13%	16.30%
Solar	29.57%	27.85%	34.59%

Source: Author´s own elaboration employing Data from European Commission (2016) and Markandya & Wilkinson (2007)

Nevertheless, the fact that an energy generation source in the mix is limited to the threshold mentioned before suggests a strong preference of that source in the energy portfolio, in other words, the energy source(s) that reaches the threshold is (are) considered to be the most efficient within the mix and cannot be used as much as the model would have to if that restriction did not exist. If the model limits the share of the source in the minimum risk portfolio or the minimum generation cost of electricity portfolio, the source will be the most efficient in terms of risk or cost. However, if the source is limited by the threshold in every portfolio along the Efficient

Portfolio Frontier, this source of power will be most efficient, being the one with a lower risk and cost.

Thus, it can give an idea of what will be the leading energy production technology for the next years as well as to where the stream of investments will flow.

4.3.2 Uniqueness Constraint

Make a simplified estimation, it will be assumed that the country produces exactly 100% of the power it consumes, having neither shortages nor surplus of electricity and no power trade with other countries. The sum of all fractional share of energy technologies will be equal to 1, and no technology can have a negative share in the electricity production.

4.3.3 Energy Poverty

Having an accessible electricity supply is one of the main concerns of the German and European authorities (as stated in the European Green Deal), for this reason, the model must set a certain limit for the electricity price.

The purpose of having an affordable electricity household price is to reduce the country´s energy poverty, the price of the electricity is directly related with energy poverty of any nation, however, in the German case after running a correlation analysis (made by the authors of this project), no clear correlation was observed between those variables, neither comparing the share of energy poverty in every percentile of the income distribution (in terms of Arrears on Utility Bills and Inability to keep home adequately warm) with the electricity household price, nor comparing the electricity household price with the share of energy poverty of the four energy poverty indicators (Arrears on Utility Bills, High share of energy expenditure in income, Inability to keep home adequately warm and Low absolute expenditure). The fact that this relation is not clear is explained by several variables such as the price of other energy inputs charged in the utility bills (such as gas or oil), the change in the subsidies granted to low-income households or the change in the energy efficiency of homes (among other variables).

The threshold for the portfolio power generation cost is defined as 110% of the total cost of the 2018 portfolio (Table 9), all portfolios that have higher power costs, even if they are located in the Efficient Portfolio Frontier will be erased from this model.

Table 9. *Germany´s Electricity Production Portfolio (2018)*

Nuclear	11.84%
Coal	35.53%
Gas	14.68%
Oil	0.80%
Onshore Wind	13.70%
Grand Scale Hydro	3.61%
Mini-Hydro	0.87%
Offshore Wind	3.42%
Biofuels	7.90%
Solar	7.65%
RES Total	37.15%
Risk	2.66 Euros/MWh
Cost	82.64 Euros/MWh

Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020)

4.4 Markowitz´s Model Outcomes

After running the model, three forecasts were generated, one for each time frame (2030, 2040 and 2050).

4.4.1 2030, 2040 & 2050 Efficient Frontiers Comparison

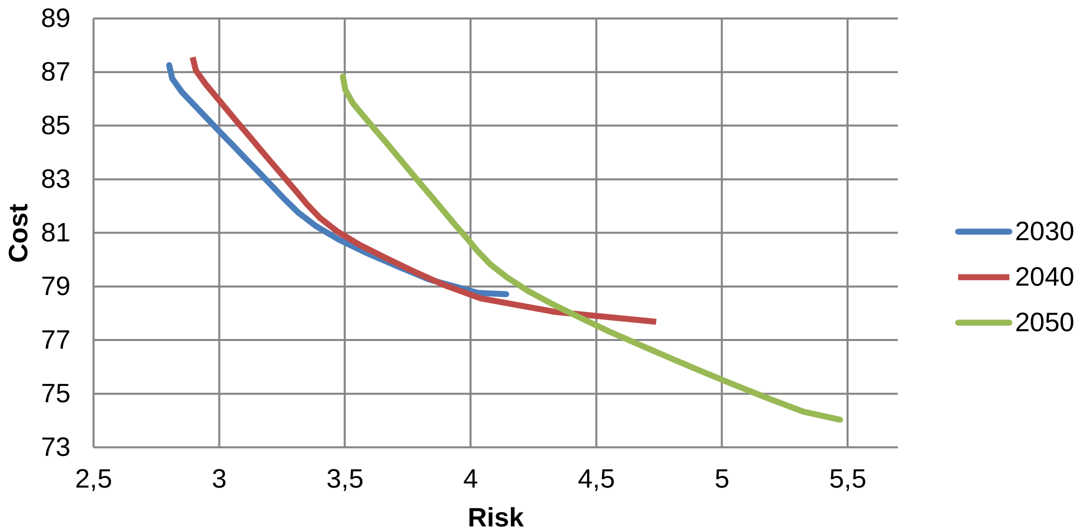
Only a minor improvement can be observed from 2030 to 2040, Green Energy Sources are more competitive and offer a new range of cost-efficient portfolios (Figure 15).

By 2050, most of the power produced in the country is generated through green energy sources, that even though they cannot be as risk aversive as the frontiers of

2030 and 2040, they can lead to a much lower production cost. Notwithstanding, this problem is expected to disappear in the decades beyond 2050, considering the risk is defined as the change of production costs, due to the fact that a sudden drop in generation prices is likely to happen from 2030 to 2050 and it is expected to stabilize as the time passes, which will be considered as a much more stable and inexpensive frontier (and therefore more efficient) than the previous ones.

Conventional Energy Sources, especially coal, are strong components throughout the 30 years of study since CO_2 emission fees are not included in the calculus. Otherwise, the competitiveness of these sources will be highly reduced since the emissions are heavily taxed in the EU, especially as time passes. Subsequently, the weight of this sources in the electricity mix may not be as large as it is in the model.

Figure 15. *2030, 2040 & 2050 Efficient Portfolio Frontier (in Euros/MWh)*



Author´s Own Elaboration

4.4.2 2030 Efficient Frontier

As seen in the Table 10, all portfolios for this scenario sticks to the minimum share of RES in the electricity mix (65%), this may indicate that the RES are not mature enough to meet such a strong requirement and it need more years to be competitive regarding the production cost.

Coal and Gas are the most efficient energy sources in terms of cost and risk, they both are limited by the maximum threshold throughout all portfolios, indicating that is the preferred technology for this horizon (Annex B).

When it comes to Green Energy Sources, Solar seems to be constantly over all portfolios. Biofuels, Hydro and Offshore Wind are slanted towards risk efficient portfolios and Onshore Wind towards cost efficient portfolios.

Table 10. *Germany´s 2030 Efficient Portfolios: RES, Risk and Cost*

	RES Total	Risk (Euros/MWh)	Cost (Euros/MWh)
Portfolio 1	65.01%	2.80	87.26
Portfolio 2	65.01%	2.81	86.76
Portfolio 3	65.01%	2.85	86.26
Portfolio 4	65.01%	2.90	85.76
Portfolio 5	65.01%	2.95	85.26
Portfolio 6	65.01%	3.00	84.76
Portfolio 7	65.01%	3.06	84.26
Portfolio 8	65.01%	3.11	83.76
Portfolio 9	65.01%	3.16	83.26
Portfolio 10	65.01%	3.21	82.76
Portfolio 11	65.01%	3.26	82.26
Portfolio 12	65.01%	3.31	81.76
Portfolio 13	65.01%	3.38	81.26
Portfolio 14	65.01%	3.47	80.76
Portfolio 15	65.01%	3.58	80.26
Portfolio 16	65.01%	3.71	79.76
Portfolio 17	65.01%	3.83	79.26
Portfolio 18	65.01%	4.03	78.76
Portfolio 19	65.01%	4.14	78.71

Author´s Own Elaboration

4.4.3 2040 Efficient Frontier

By 2040, RES and Biofuels are still not as developed. The share of RES in almost all portfolios is the minimum required by the German Climate Action Programme

2030. However, a slight improvement can be seen in the last three cost extreme portfolios that show the technology is competitive enough (in terms of cost) to be preferred over Conventional Energy Sources in the model (Table 11).

Coal is still the most efficient energy source in terms of cost and risk, nevertheless, gas is not always preferred by the model in all portfolios, in low cost points it is substituted by Green Energy Sources.

Offshore Wind is consolidated as a stable electricity sources in all portfolios and Hydro and Biofuels still have low risk bias behavior (Annex C).

***Table 11**. Germany´s 2040 Efficient Portfolios: RES, Risk and Cost*

	RES Total	Risk (Euros/MWh)	Cost (Euros/MWh)
Portfolio 1	65.00%	2.89	87.55
Portfolio 2	65.00%	2.91	87.05
Portfolio 3	65.00%	2.94	86.55
Portfolio 4	65.00%	2.99	86.05
Portfolio 5	65.00%	3.03	85.55
Portfolio 6	65.00%	3.08	85.05
Portfolio 7	65.00%	3.12	84.55
Portfolio 8	65.00%	3.17	84.05
Portfolio 9	65.00%	3.21	83.55
Portfolio 10	65.00%	3.26	83.05
Portfolio 11	65.00%	3.30	82.55
Portfolio 12	65.00%	3.35	82.05
Portfolio 13	65.00%	3.40	81.55
Portfolio 14	65.00%	3.47	81.05
Portfolio 15	65.00%	3.56	80.55
Portfolio 16	65.00%	3.66	80.05
Portfolio 17	65.00%	3.77	79.55
Portfolio 18	65.01%	3.89	79.05
Portfolio 19	67.82%	4.04	78.55
Portfolio 20	72.32%	4.33	78.05
Portfolio 21	82.18%	4.74	77.68

Author´s Own Elaboration

4.4.4 2050 Efficient Frontier

2050 is the year when a big improvement RES can be observed. Even though the required production by Green Energy Sources is now 80%, the extreme cost portfolios surpasses this mark, pushing 90% of the electricity generation in the country (Table 12).

Onshore Wind has gained a lot of importance in the electricity mix, being by far the largest energy source and Coal is still the most efficient energy source in terms of cost and risk (Annex D).

***Table 12**. Germany´s 2050 Efficient Portfolios: RES, Risk and Cost*

	RES Total	Risk (Euros/MWh)	Cost (Euros/MWh)
Portfolio 1	80.00%	3.49	86.83
Portfolio 2	80.00%	3.50	86.33
Portfolio 3	80.00%	3.53	85.83
Portfolio 4	80.00%	3.58	85.33
Portfolio 5	80.00%	3.62	84.83
Portfolio 6	80.00%	3.67	84.33
Portfolio 7	80.00%	3.71	83.83
Portfolio 8	80.00%	3.76	83.33
Portfolio 9	80.00%	3.80	82.83
Portfolio 10	80.00%	3.85	82.33
Portfolio 11	80.00%	3.89	81.83
Portfolio 12	80.00%	3.94	81.33
Portfolio 13	80.00%	3.98	80.83
Portfolio 14	80.00%	4.02	80.33
Portfolio 15	80.00%	4.08	79.83
Portfolio 16	80.00%	4.14	79.33
Portfolio 17	80.00%	4.23	78.83
Portfolio 18	80.00%	4.33	78.33
Portfolio 19	80.00%	4.44	77.83
Portfolio 20	80.00%	4.55	77.33
Portfolio 21	80.88%	4.67	76.83
Portfolio 22	82.59%	4.79	76.33
Portfolio 23	84.30%	4.92	75.83
Portfolio 24	86.02%	5.05	75.33
Portfolio 25	87.73%	5.18	74.83
Portfolio 26	89.53%	5.32	74.33
Portfolio 27	89.53%	5.47	74.03

Author´s Own Elaboration

4.4.5 Health Index Evolution

In order to calculate the health effects of the power production of the Efficient Frontier the share of each technology in each portfolio will be multiplied by the projected production (Table 13) and by the cases per TWh of the Table 5.

Table 13. *Germany´s Projected Electricity Production (2030-2050)*

Year	TWh
2030	610.83
2040	617.69
2050	647.22

Source: European Commission (2016)

The outcome of this factor will be a spread of maximum and minimum cases per efficient frontier. Nevertheless, even if we consider the worst-case scenario, in which we select the upper part of the spread and compare it to the cases of 2018 the results are clear that in each and every time frame deaths, serious illness and minor illness are reduced, achieving by 2050 a 3-factor reduction in all cases (Table 14).

Table 14. *Projected air pollution effects by electricity source in Germany*

Year		Deaths	Serious Illness	Minor Illness
2030	**Minimum**	4,505	41,536	2,387,203
	Maximum	4,808	44,355	2,536,425
	Arithmetic Mean	4,754	43,850	2,509,690
2040	**Minimum**	3,264	29,876	1,769,809
	Maximum	3,464	31,981	1,827,305
	Arithmetic Mean	3,747	34,758	1,941,402
2050	**Minimum**	2,008	18,384	1,089,016
	Maximum	2,542	23,587	1,309,825
	Arithmetic Mean	2,363	21,887	1,228,433

Source: Author´s own elaboration employing Data from Markandya & Wilkinson (2007)

Conclusions

Germany is in the way to complete its Energy Transition. Having heavily invested in Renewable Energy Sources over the last decades, the country is a reference in Green Energy Production worldwide. Being the largest energy consumer and electricity producer in Europe, and thanks to its location in Central Europe, the nation is the energy front runner in the EU landscape and the first major green economy in the world.

Despite the fact of being extremely dependent on foreign fossil fuels such as the Russian natural gas and having a long-lasting coal mining tradition, the country has managed to transition from a centralized coal-based energy market to a decentralized renewable economy. This change has happened thanks to the firm policies such as the nuclear phase-out or the green electricity surcharges carried out by the national and European authorities.

Moreover, the electricity production´s future seems to be even brighter, it is expected that Renewable Energy Sources and Biofuels will become the main technologies to generate power, bringing many positive externalities such as a drop in electricity prices, a more secure and stable energy mix, an electrification of the economy, an environmentally friendly production and a healthier lifestyle.

According to the Markowitz model of the thesis, by 2030, 65% of the electricity produced in the country will be generated by RES and Biofuels, by 2040, 65%-82% will be green power, and by 2050 this proportion will reach 80%-90%. As the energy transition advances in the timeframe of study, Conventional Energy Sources are expected to be less important and even disappear from the electricity mix as it happens with nuclear power. In contrast, all Green Energy Sources will be improved drastically, being way more competitive in terms of production cost than fossil fuel Sources, indeed, Onshore Wind will become the single largest energy source, generating 31%-65% of power in the country, followed by Solar (13%-28%).

Without any doubt many countries will follow Germany´s policies to achieve the needed energy transition, therefore knowing and understanding the German case now will help to explain the future actions of developed and emerging economies in this regard.

Annexes

Annex A

Table 15. *Energy Units Conversion Table*

	Watt hour (Wh)	Kilowatt Hour (kWh)	Megawatt Hour (MWh)	GigaWatt Hour (GWh)	Terawatt Hour (TWh)	Tonnes of oil Equivalent (toe)	Million Tonnes of oil Equivalent (Mtoe)
Watt hour (Wh)	1	0.001	0.000001	0.000000001	1E-12	8.59845E-08	8.59845E-14
Kilowatt Hour (kWh)	1,000	1	0.001	0.000001	0.000000001	8.59845E-05	8.59845E-11
Megawatt Hour (MWh)	1,000,000	1,000	1	0.001	0.000001	0.085984523	8.59845E-08
GigaWatt Hour (GWh)	1E+09	1,000,000	1,000	1	0.001	85.98452279	8.59845E-05
Terawatt Hour (TWh)	1E+12	1,000,000,000	1,000,000	1,000	1	85,984.52279	0.085984523
Tonnes of oil Equivalent (toe)	11,630,000	11,630	11.63	0.01163	0.00001163	1	0.000001
Million Tonnes of oil Equivalent (Mtoe)	1.163E+13	1.163E+10	11,630,000	11,630	11.63	1,000,000	1

Author´s Own Elaboration

Annex B

***Table 16**. Germany´s 2030 Efficient Frontier Portfolios (in percentage)*

	Coal	Gas	Onshore Wind	Offshore Wind	Grand Scale Hydro	Mini-Hydro	Biofuels	Solar
Portfolio 1	23.82	11.17	24.11	5.88	8.96	2.68	10.73	12.65
Portfolio 2	23.82	11.17	26.63	4.76	8.96	2.68	10.09	11.89
Portfolio 3	23.82	11.17	29.15	3.63	8.96	2.68	9.46	11.13
Portfolio 4	23.82	11.17	29.77	3.71	7.92	2.68	9.59	11.35
Portfolio 5	23.82	11.17	30.37	3.78	6.87	2.68	9.73	11.58
Portfolio 6	23.82	11.17	30.97	3.86	5.82	2.68	9.87	11.81
Portfolio 7	23.82	11.17	31.57	3.94	4.77	2.68	10.01	12.03
Portfolio 8	23.82	11.17	32.18	4.02	3.72	2.68	10.15	12.26
Portfolio 9	23.82	11.17	32.78	4.1	2.67	2.68	10.29	12.49
Portfolio 10	23.82	11.17	33.38	4.18	1.62	2.68	10.43	12.72
Portfolio 11	23.82	11.17	33.98	4.26	0.57	2.68	10.57	12.94
Portfolio 12	23.82	11.17	35.46	3.79	0	2.68	10.36	12.72
Portfolio 13	23.82	11.17	37.98	2.67	0	2.68	9.72	11.96
Portfolio 14	23.82	11.17	40.5	1.55	0	2.68	9.08	11.2
Portfolio 15	23.82	11.17	43.02	0.43	0	2.68	8.44	10.44
Portfolio 16	23.82	11.17	45.19	0	0	1.52	8.15	10.15
Portfolio 17	23.82	11.17	47.37	0	0	0	7.83	9.81
Portfolio 18	23.82	11.17	50.18	0	0	0	2.87	11.96
Portfolio 19	23.82	11.17	50.18	0	0	0	0	14.83

Author´s Own Elaboration

Annex C

Table 17. *Germany´s 2040 Efficient Frontier Portfolios (in percentage)*

	Coal	Gas	Onshore Wind	Offshore Wind	Grand Scale Hydro	Mini-Hydro	Biofuels	Solar
Portfolio 1	17.82	17.18	24.15	5.88	9.19	2.75	10.36	12.67
Portfolio 2	17.82	17.18	26.76	5.06	9.19	2.75	9.22	12.02
Portfolio 3	17.82	17.18	28.81	4.49	8.94	2.75	8.43	11.59
Portfolio 4	17.82	17.18	29.35	4.58	7.98	2.75	8.54	11.81
Portfolio 5	17.82	17.18	29.88	4.66	7.03	2.75	8.66	12.02
Portfolio 6	17.82	17.18	30.42	4.75	6.07	2.75	8.77	12.24
Portfolio 7	17.82	17.18	30.96	4.84	5.12	2.75	8.89	12.45
Portfolio 8	17.82	17.18	31.49	4.92	4.17	2.75	9	12.67
Portfolio 9	17.82	17.18	32.03	5.01	3.21	2.75	9.12	12.88
Portfolio 10	17.82	17.18	32.57	5.1	2.26	2.75	9.24	13.09
Portfolio 11	17.82	17.18	33.1	5.19	1.3	2.75	9.35	13.31
Portfolio 12	17.82	17.18	33.64	5.27	0.35	2.75	9.47	13.52
Portfolio 13	17.82	17.18	35.49	4.79	0	2.75	8.79	13.19
Portfolio 14	17.82	17.18	38.1	3.97	0	2.75	7.66	12.53
Portfolio 15	17.82	17.18	40.7	3.15	0	2.75	6.53	11.87
Portfolio 16	17.82	17.18	42.76	2.77	0	1.75	6	11.72
Portfolio 17	17.82	17.18	44.4	2.73	0	0	5.92	11.95
Portfolio 18	17.82	17.16	47	1.91	0	0	4.79	11.31
Portfolio 19	17.82	14.35	48.51	1.47	0	0	3.56	14.29
Portfolio 20	17.82	9.86	48.51	0.8	0	0	1.04	21.96
Portfolio 21	17.82	0	48.51	5.82	0	0	0	27.85

Author´s Own Elaboration

Annex D

Table 18. *Germany´s 2050 Efficient Frontier Portfolios (in percentage)*

	Coal	Gas	Onshore Wind	Offshore Wind	Grand Scale Hydro	Mini-Hydro	Biofuels	Solar
Portfolio 1	10.47	9.53	31.21	7.6	9.83	2.94	12.04	16.38
Portfolio 2	10.47	9.53	33.62	6.94	9.83	2.94	10.68	15.99
Portfolio 3	10.47	9.53	36.03	6.28	9.83	2.94	9.32	15.6
Portfolio 4	10.47	9.53	36.93	6.21	9.12	2.94	9.11	15.69
Portfolio 5	10.47	9.53	37.43	6.3	8.23	2.94	9.22	15.9
Portfolio 6	10.47	9.53	37.92	6.39	7.33	2.94	9.32	16.11
Portfolio 7	10.47	9.53	38.42	6.47	6.43	2.94	9.42	16.32
Portfolio 8	10.47	9.53	38.92	6.56	5.53	2.94	9.52	16.53
Portfolio 9	10.47	9.53	39.42	6.65	4.63	2.94	9.63	16.74
Portfolio 10	10.47	9.53	39.92	6.74	3.73	2.94	9.73	16.95
Portfolio 11	10.47	9.53	40.42	6.82	2.83	2.94	9.83	17.16
Portfolio 12	10.47	9.53	40.92	6.91	1.94	2.94	9.93	17.37
Portfolio 13	10.47	9.53	41.42	7	1.04	2.94	10.04	17.58
Portfolio 14	10.47	9.53	41.92	7.08	0.14	2.94	10.14	17.79
Portfolio 15	10.47	9.53	44.03	6.54	0	2.94	9	17.5
Portfolio 16	10.47	9.53	46.44	5.88	0	2.94	7.64	17.1
Portfolio 17	10.47	9.53	48.85	5.22	0	2.94	6.28	16.72
Portfolio 18	10.47	9.53	51.26	4.56	0	2.94	4.91	16.33
Portfolio 19	10.47	9.53	53.08	4.36	0	1.74	4.39	16.42
Portfolio 20	10.47	9.53	54.64	4.37	0	0	4.25	16.73
Portfolio 21	10.47	8.65	56.79	4	0	0	3.41	16.68
Portfolio 22	10.47	6.94	58.68	3.91	0	0	3.06	16.94
Portfolio 23	10.47	5.23	60.58	3.82	0	0	2.71	17.2
Portfolio 24	10.47	3.52	62.48	3.73	0	0	2.35	17.46
Portfolio 25	10.47	1.81	64.37	3.64	0	0	2	17.72
Portfolio 26	10.47	0	65.19	3.72	0	0	0.63	19.99
Portfolio 27	10.47	0	65.19	0	0	0	0	24.34

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